Control of Contact Dynamics Between Flexible Wire and Rigid Body for Orbital Target Capture

著者	?橋 一平
号	59
学位授与機関	Tohoku University
学位授与番号	工博第5036号
URL	http://hdl.handle.net/10097/62786

氏　　　　　名	たかはし　いっぺい 髙　橋　一　平
授　与　学　位	博士（工学）
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指　導　教　員	東北大学教授　内山　勝
論文審査委員	主査　東北大学教授　内山　勝　　東北大学教授　吉田　和哉 東北大学教授　橋本　浩一

論文内容要旨

Various space explorations have been operated since first satellite was launched half century ago. Especially, orbital operations around the earth are focused on because these works are directly related to our daily life on earth, for example, a weather satellite, communications satellite, and so on. Therefore many orbital operations have been planned and actively executed, and it is expected that it becomes more important to execute the orbital work in the future.

A reliability is the most important for the orbital activity. The capture in enclosed region is known as one of the most safe and reliable capture methods. This capture method is achieved with the Latching End effector (LEE) mounted on the tip of space manipulator and the Grapple Fixture (GF) mounted on the floating target. There are two strong advantages in this capture method. One is that it is not required to precisely align the capture position of the end effector with that of the target. Another is that it is capable to avoid pushing the target away by the manipulator. Therefore, this capture mechanism has ever been used in various orbital operations using the Shuttle Remote Manipulator System (SRMS) or Space Station Remote Manipulator System (SSRMS). On the other hand, this capture method has been only used in capturing the floating target under the conditions as follows:

1. Target mass is large.
2. Position and attitude of the target are able to be controlled.
3. Flexible joint manipulator is used.
4. There is almost no relative motion between the tip of manipulator and the floating target.
5. Criteria of the relative motion for capturing the floating target safely is severely set.

These conditions are required to capture the floating target safely, especially, fifth condition is important to capture the orbital target safely. If these restricted conditions can be decreased, it is expected that this capture method can be applied to the various orbital operations.

From the above, the aim of this research is to construct the contact control for capturing the orbital target by the flexible joint manipulator mounting the capture mechanism in enclosed region on.

In order to achieve the aim of this research, following two demands to be solved:

1. Relative motion between the latching end effector and grapple fixture after the contact occurred shall be clarified in orbital operation.

2. The contact control for capturing a floating target without pushing it away shall be proposed.

Because the first demand is required to solve the second demand, the experiment for clarifying the relative behavior between the LEE and the floating target is carried out.

Then, the contact control for stable and reliable capture is proposed in the basis of the result of the experiment for first demand.

First, the simulator was developed for capturing the HTV by the flexible space manipulator mounted on ISS, and the experiment was executed in order to fulfill the first demand. In this research, HTV mission in which the commodities were transferred to the international space station (ISS) was selected as an orbital operation. In general, it is known that the numerical simulation, the experiment using the real mechanism or its mockup and the hardware in the loop simulation are as the methods for simulating the orbital operations on the ground. In this research, a hybrid motion simulator (HMS) which is a kind of the hardware in the loop simulator is used because the flexible wire mounted on the LEE has complex characteristic which is difficult to accurately model in the numerical simulation. The HMS can simulate three dimensional relative motion between two objects, such as a space robot and a floating target, under the microgravity environment on the ground. Basically, HMS is the numerical simulator, but the contact part of capture mechanism in numerical simulation is replaced to the mockup. This is because it avoids modelling the complex phenomenon such as the multi-point contact or collision. Therefore, it is capable of avoiding modelling the flexible wire which had the complex physical characteristic. In developing this simulator, it was required to construct the physical model and the numerical model. The half-scaled mockups of LEE and GF were developed as the physical model in the HMS. The entire dynamic models of the SSRMS and HTV were constructed as the numerical model in the HMS. Here, because the physical models were scaled down, the dynamic models were also scaled down by the similarity rule between real and numerical models. Therefore, the similarity rule was derived using the non-dimensional motion equation of the HTV and SSRMS. In order to verify this similarity rule, the numerical simulations were executed by using one DOF flexible joint manipulator and the SSRMS model which was seven DOF flexible joint manipulator, and the results clearly showed that the similarity rule was valid. Here, the HMS developed in our laboratory has the inherent problem about the delay time. Therefore, in order to evaluate the stability of the developed simulator for HTV mission, the frequency analysis of the contact dynamics was carried out and the coefficient of restitution (COR) was analyzed. From these analyses, it was found that the stiffness in the

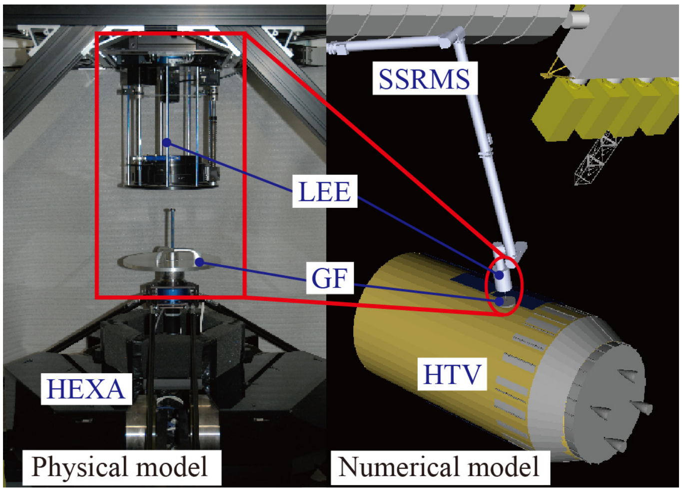

Fig. 1 Developed simulator for HTV mission

each experimental condition satisfied the criterion for stable HMS. Additionally, in HMS, it was known that the COR of the contact between rigid bodies exceeded 1 when the target mass is 2000 [kg]. However, it was found from the contact experiment between a flexible wire and a rigid body that the COR under each condition was lower than 1. Therefore, the HMS has enough capability for the HTV capture simulation. The contact experiments under two situations were executed by the developed simulator. In the first situation, the joint control called LIMP mode was applied to SSRMS. The LIMP mode is always applied to SSRMS just before contacting the GF shaft with the flexible wire. In the second situation, no control was applied to SSRMS. In this situation, SSRMS showed the characteristic of the flexible joint manipulator. It is required to clarify the relative behavior in both situations in order to propose the contact control for safe and reliable capture and avoid the orbital accident. With respect to the first situation, the experimental result under the initial condition from the initial reference data before the contact occurred was compared with the reference data calculated from the real flight data. It was found from this comparison that the characteristics of behavior and contact force under this condition were almost same as the one second of the movement and the one sixteen of the external force from the estimated data. Next, the experiments under five conditions were executed in order to verify the relative behavior after the contact occurred and the criteria of maximum initial velocity. From these experimental results, the characteristic of the relative behavior after the contact and the criteria of allowable initial target velocity were clarified. Additionally, it was found that the capture tended to fail if the contact force was larger in the enclosed region. With respect to the second situation, the characteristic of flexible joint manipulator such as SSRMS was confirmed first. Then, the experiment of HTV mission was executed in the state of flexible joint, and the results are discussed. It was found from these results that the vibration of the tip of flexible joint manipulator affected the stable capture in enclosed region largely. Moreover, it was found that the large contact force occurred when the capture failed. Here, LIMP mode is not the active contact control to succeed the stable capture for the floating target. Additionally, it is dangerous if the accidental contact occurs in the situation not applying the LIMP mode.

From the above contact experiment, it was required for the proposed contact control to capture the floating target as follows:

1. Controlling the vibration at the tip of flexible joint manipulator.
2. Keeping contact between the flexible wire and the floating target.
3. Controlling the contact force between flexible wire and the floating target.

Especially, third requirement is important because the contact force increases exponentially as the pushing quantity increases. Here, the hand impedance control is known as the valid method for capturing the floating target under the microgravity environment. Therefore, the contact control based on the impedance control for flexible joint manipulator was proposed. In order to apply this control to the flexible joint manipulator, the torque controller proposed in the previous work was used. This torque controller achieved the desired joint torque for presenting the desired impedance at the tip of flexible joint manipulator. However, it was not enough to apply only this method to the flexible joint manipulator in order to fulfill the second and third requirements. Here, in order to achieve the desired contact control, it is necessary to tune the two parameters of the impedance control properly. One is the parameter tuning of the impedance damping coefficient for keeping contacting the flexible wire with the floating target, another was the parameter tuning of the impedance stiffness coefficient for keeping the characteristic of relative motion between the tip of flexible joint manipulator and the floating target in any target property. Especially, the latter was important for capture by using the flexible wire to control the contact force between the flexible wire and the floating target. The latter tuning method was to derive the impedance stiffness coefficient as a variable including the variable contact stiffness. If these parameter tunings are applied to the contact control, it is possible to control the contact force and keep contacting with the flexible wire and the target.

Then, the various contact simulations by one DOF flexible joint manipulator and three DOF flexible joint manipulator were executed. First, the two types of simulations were executed in order to confirm the validity of the proposed contact control. One was the case of applying only the hand impedance control to the flexible joint manipulator, another was the case of applying the proposed contact control to the flexible joint manipulator. These results clearly showed that the proposed contact control was effective to capture the floating target by the flexible joint manipulator stably. After that, the simulations applied the proposed contact control were executed in order to confirm the validity of the parameter tuning for the impedance stiffness coefficient under the various conditions. The results from the proposed tuning of the variable impedance stiffness coefficient were compared with the results in the case of a constant impedance stiffness coefficient when the target mass was changed. It was found from this comparison that the proposed parameter tuning for impedance stiffness coefficient was also effective to keep the maximum contact force when the target mass changed. From the above results and discussions, it was clearly shown that the proposed contact control was effective to capture the floating target by the flexible joint manipulator under the microgravity environment.

In short, the two researches were executed in this research as follows:

1. Developing the hybrid motion simulator for orbital operation using the capture in enclosed region.
2. Proposing the contact control which can capture the floating target by the flexible joint manipulator safely.

The former was the first time in the world to develop the hybrid motion simulator for capturing the massive target by the flexible joint manipulator mounting the capture mechanism in enclosed region on.

It is expected that this simulator can be used in the pre-verifying of the orbital mission using the capture in the enclosed region before launch.

On the other hand, it is expected that the latter is used when the method for avoiding occurring the orbital accident is proposed.

Additionally, it is expected that the proposed contact control is used in proposing the method for orbital servicing robot which can refuel the satellite and deorbiting the space debris.

論文審査結果の要旨

近年の宇宙開発では，軌道上作業の重要性が非常に高まっており，安全かつ確実な捕獲技術の確立が求められている。軌道上作業において，現在多く用いられている捕獲手法に，閉空間把持手法がある。この閉空間把持手法では，柔軟ワイヤを有する閉空間把持機構と柔軟関節マニピュレータが用いられているが，捕獲する際に有効な接触制御は適用されてはおらず，捕獲時の条件も非常に制限的である。これに対し，本論文では，閉空間把持手法に適した接触制御を適用することにより，捕獲条件拡大と確実性向上を目指している。まず，捕獲手法の特性を知るために，捕獲ミッション評価のための地上ハイブリッドシミュレータを構築している。これを基に閉空間把持手法における接触制御手法を評価し，新たな制御手法を提案し，その有効性を検証している。本論文は，以下の内容により構成され，全編4章よりなる。

第1章は序論であり，本研究の背景・目的を述べている。

第2章では，閉空間把持手法の特性を調べるために，本手法の適用対象であるHTVミッションの模擬が可能なHTV捕獲のハイブリッドシミュレータを構築している。このシミュレータ構築では，把持機構部のハードウェアの製作と，相似則を適用した数値モデルの構築がなされている。そして，構築したシミュレータを用いて，HTV 捕獲シミュレーションを行ない，接触時の相対挙動の検証，および捕獲可能な条件の上限を確認している。これは有用な成果である。

第3章では，第2章の結果を受けて，柔軟関節マニピュレータによるターゲットの弾き飛ばしを防止し，接触力を一定に保つ接触制御を構築している。この接触制御では，インピーダンス制御を基本として，インピーダンス剛性係数を調整することで，ターゲットとマニピュレータ手先の間の相対運動を制御することを可能としている。これにより，ターゲット質量に関わらず，常に同じ大きさの接触力の実現が可能となる。ターゲット質量を変化させて接触シミュレーションを行ない，その有効性が示されている。これは，安全かつ確実な捕獲技術の確立に資する重要な成果である。

第4章は結論である。

以上要するに本論文は，捕獲手法として閉空間把持手法を用い，軌道上作業の模擬が可能な地上ハイブリッドシミュレータの開発を行ない，その結果に基づき，閉空間把持手法の確実性向上のための接触制御を構築する研究である。ハイブリッドシミュレータの従来のシミュレータに対する優位性，および構築した接触制御の従来の接触制御に対する新規性を考慮すると，機械システムデザイン工学およびロボット工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。